

# **Extra Dimensional Models and their Prospects at the LHC**

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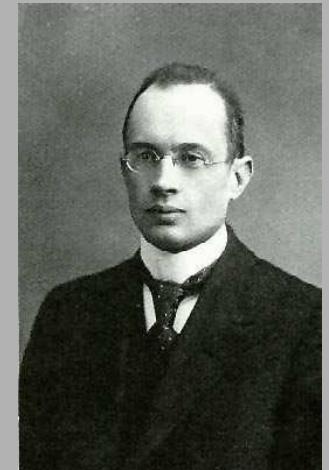
**LHC-Theory Initiative Workshop**

**October 7-8, 2010, BNL**

## Extra dimensions: 96-year old idea!

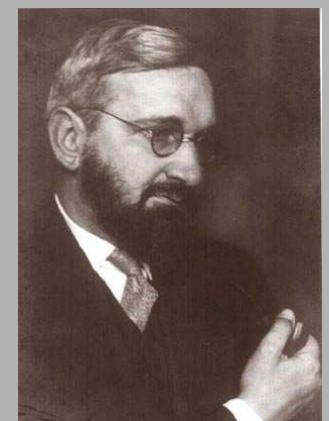
- G. Nordström, 1914:

Unify pre-GR gravity and EM in 5D.



- Th. Kaluza, 1921:

Unify GR and EM in 5D.



- O. Klein, 1926:

Unify GR and EM with one *compact* extra dimension.



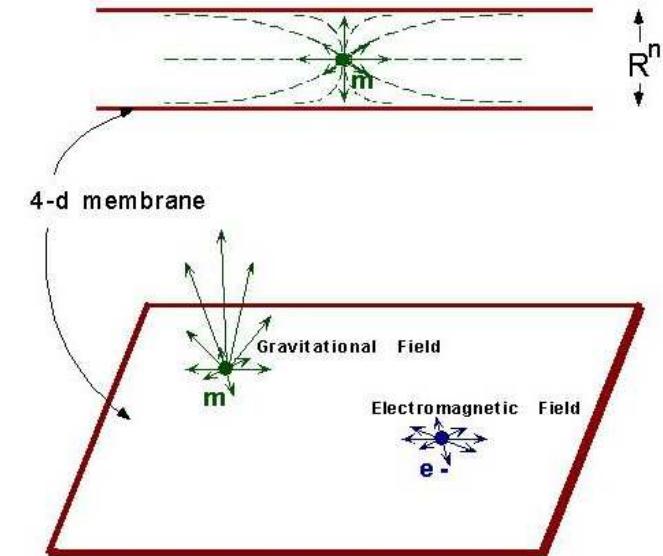
# Extra dimensions in Recent Times

- String theory, since the 1980's.
  - Quantum gravity.
  - Consistency requires 10 or 11 dimension.
  - Extra dimensions compactified near fundamental scale  $M_F$  ( $M_P \sim 10^{19}$  GeV).
- Particle Physics, since the 1990's.
  - Motivation: the hierarchy,  $m_W/M_P \sim 10^{-17}$ .
  - Antoniadis, 1990: TeV $^{-1}$  extra dimensions and SUSY breaking.
  - Weak scale superstrings, Lykken, 1996.
  - Large Extra Dimensions; Arkani-Hamed, Dimopoulos, Dvali, 1998:  $m_W \lesssim M_F$ .
  - A Warped Extra Dimension; Randall, Sundrum, 1999:  $m_W \sim e^{-k\pi r_c} M_P$ ;  $k\pi r_c \sim 35$ .
  - TeV $^{-1}$  Universal Extra Dimensions; Appelquist, Cheng, Dobrescu, 2000.
  - ...

# Large Extra Dimensions (LED)

Arkani-Hamed, Dimopoulos, Dvali, 1998

- $n$  compact extra dimensions,  $M_F \sim \text{TeV}$ :  $M_P^2 \sim R^n M_F^{n+2}$ 
  - $R \lesssim \text{mm}$  (gravity tests)  $\Rightarrow n \geq 2$ .



- SM localized on a 3-brane (4D).
- Gravity propagates in all dimensions.
  - Gravity “diluted” in extra dimensions.
- Graviton Kaluza-Klein (KK) modes.
  - Quantized momenta in extra dimensions:

$$m_{KK} = j/R; \quad j = 0, 1, 2, \dots$$

$$\mathcal{L} = \frac{-1}{M_P} T^{\mu\nu} \sum_{\{\vec{j}\}} h_{\mu\nu}^{(\vec{j})}; \quad \text{fm} \lesssim R \lesssim \text{mm}; \quad 2 \leq n \leq 6.$$

# Key Signals for LED

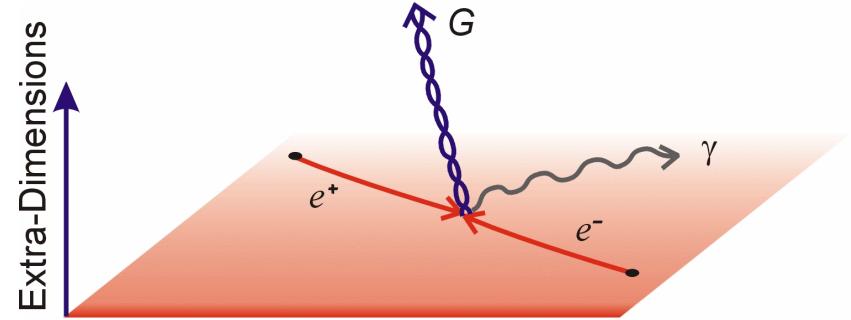
- Missing energy: KK gravitons escape into the “bulk.”

$$q\bar{q} \rightarrow j G_{KK} (\not{E}) \quad ; \quad e^+e^- \rightarrow \gamma G_{KK} \dots$$

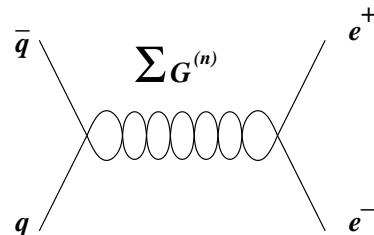
Missing  $E$  signature.

Giudice, Rattazzi, Wells 1998

Mirabelli, Perelstein, Peskin, 1998



- Virtual exchange of spin-2 tower.



Spin-2 mediated angular distributions. Han, Lykken, Zhang, 1998  
Hewett, 1998

- Black hole production for  $\sqrt{s} \gg M_F$ .

Giddings, Thomas, 2001

Dimopoulos, Landsberg, 2001

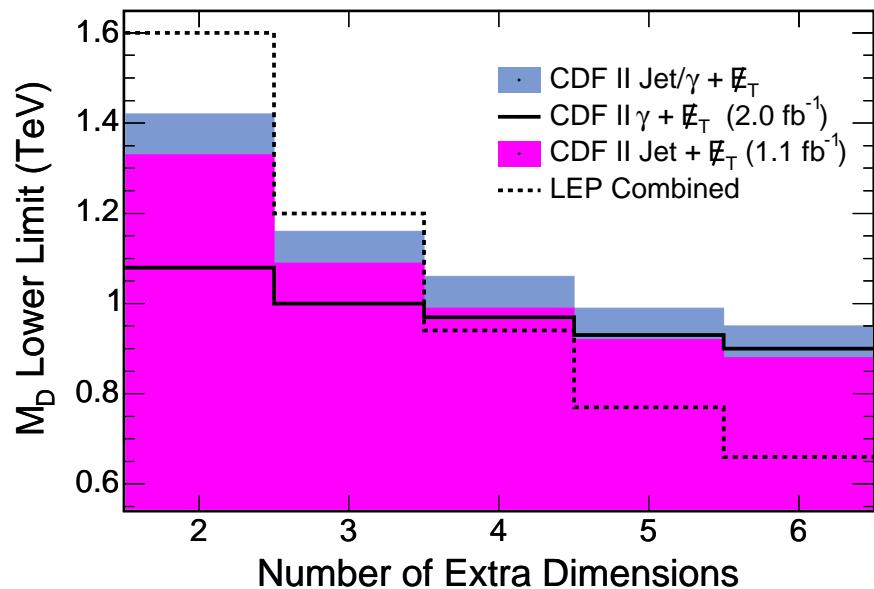
- Potentially spectacular signals: energetic multi-jets, leptons, . . . .

- Under debate.

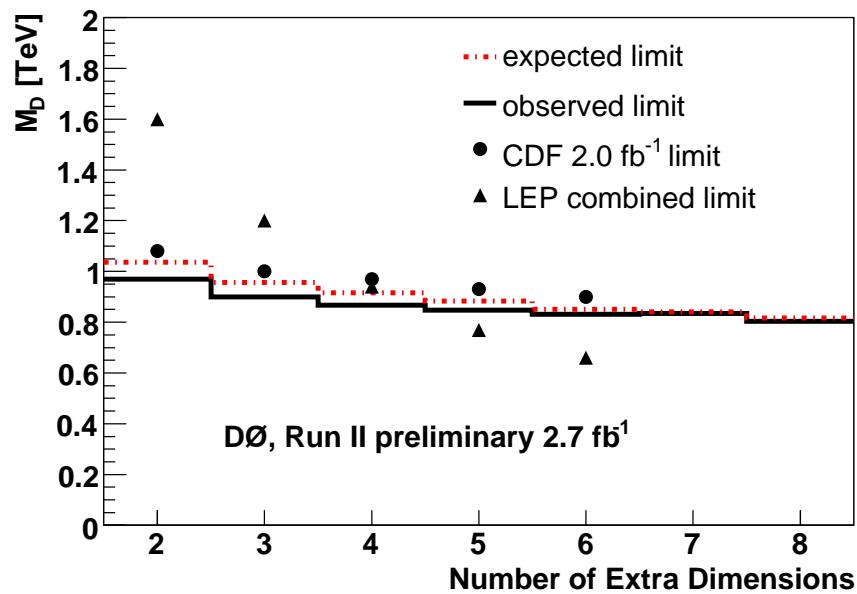
e.g. Meade, Randall, 2007:  $2 \rightarrow 2$  quantum gravity effects more likely at the LHC.

# LED: Current Bounds and Future Prospects

- Collider limits:



Jets/ $\gamma + E_T$   
CDF Collaboration (T. Aaltonen et al.),  
Phys.Rev.Lett.101:181602,2008



DØ Collaboration;  $\gamma + E_T$

DØ Note 5729-CONF, 2008

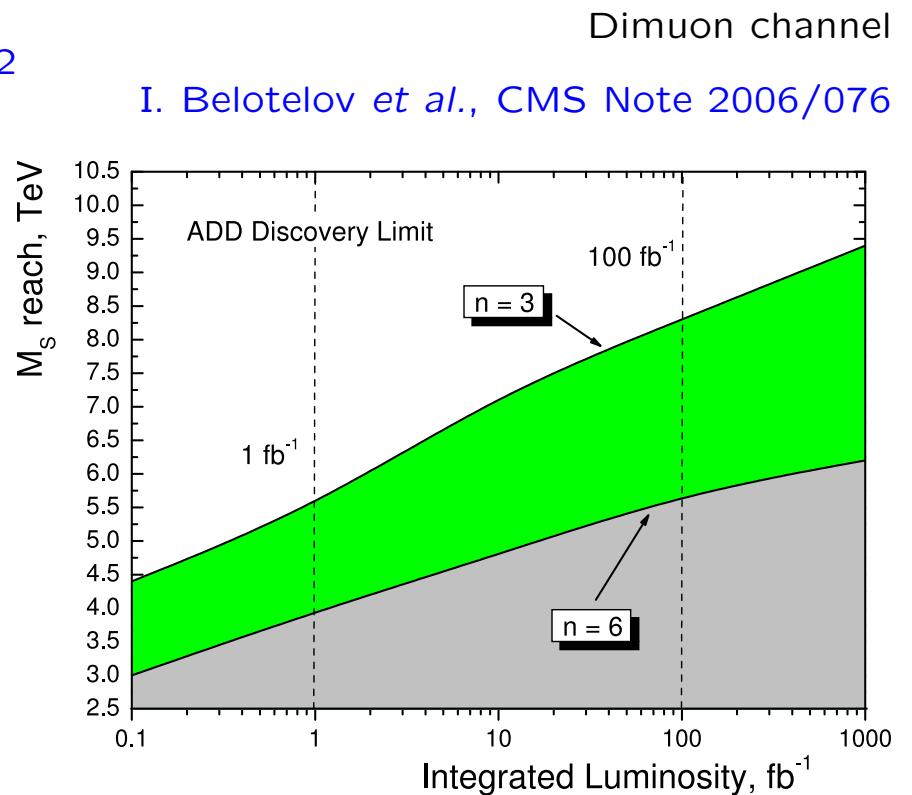
- Cosmology and Astrophysics: Arkani-Hamed, Dimopoulos, Dvali, 1998

- Cosmology: Typically  $T_{reheat} \lesssim 1$  GeV for  $M_F \sim 1$  TeV.
- SN 1987A, energy loss:  $M_F \gtrsim 50$  TeV for  $n = 2$ .  
Cullen, Perelstein, 1998
- Neutron star, excess heat from KK-could:  $M_F \gtrsim 700(30)$  TeV,  $n = 2(3)$ .  
Hannestad, Raffelt, 2001 & 2003

- $5\sigma$  LHC reach:

Kabachenko, Miagkov, Zenin, ATL-PHYS-2001-012

channel	n		2	3	4	5
$\gamma\gamma$	luminosity	$M_S^{max}$ (TeV)	6.3	5.6	5.1	4.9
	$10 \text{ fb}^{-1}$	S/B	36/18	36/18	39/25	34/13
	$100 \text{ fb}^{-1}$	$M_S^{max}$ (TeV)	7.9	7.3	6.7	6.3
		S/B	50/53	62/96	55/72	51/53
$l^+l^-$	$10 \text{ fb}^{-1}$	$M_S^{max}$ (TeV)	6.6	5.9	5.4	5.1
		S/B	33/11	31/8	30/6	30/6
	$100 \text{ fb}^{-1}$	$M_S^{max}$ (TeV)	7.9	7.5	7.0	6.6
		S/B	49/48	38/21	36/16	29/6
$\gamma\gamma + l^+l^-$	$10 \text{ fb}^{-1}$	$M_S^{max}$ (TeV)	7.0	6.3	5.7	5.4
	$100 \text{ fb}^{-1}$	$M_S^{max}$ (TeV)	8.1	7.9	7.4	7.0



# Universal Extra Dimensions (UED)

Appelquist, Cheng, Dobrescu, 2000

- All SM in  $\text{TeV}^{-1}$  extra dimensions.
- Bulk momentum conservation: 4D KK number preserved.
  - KK particles not singly produced.
  - Only loop contributions to EW precision data.
  - Less stringent bounds on  $1/R$ .
- Chiral fermions via  $\mathbb{Z}_2$  orbifolds: KK number  $\rightarrow$  KK-parity.
- Compactification: Lorentz violation along extra dimensions.
  - Loops around compact directions:  $\delta m_{KK}$ .  
Cheng, Matchev, Schmaltz, 2002
  - Lightest KK particle (LKP) stable, dark matter candidate.
  - Can mimic supersymmetry at the LHC!  
Cheng, Matchev, Schmaltz, 2002

# UED: Current Status and LHC Prospects

- EW precision: Flacke, Hooper, March-Russell, 2006

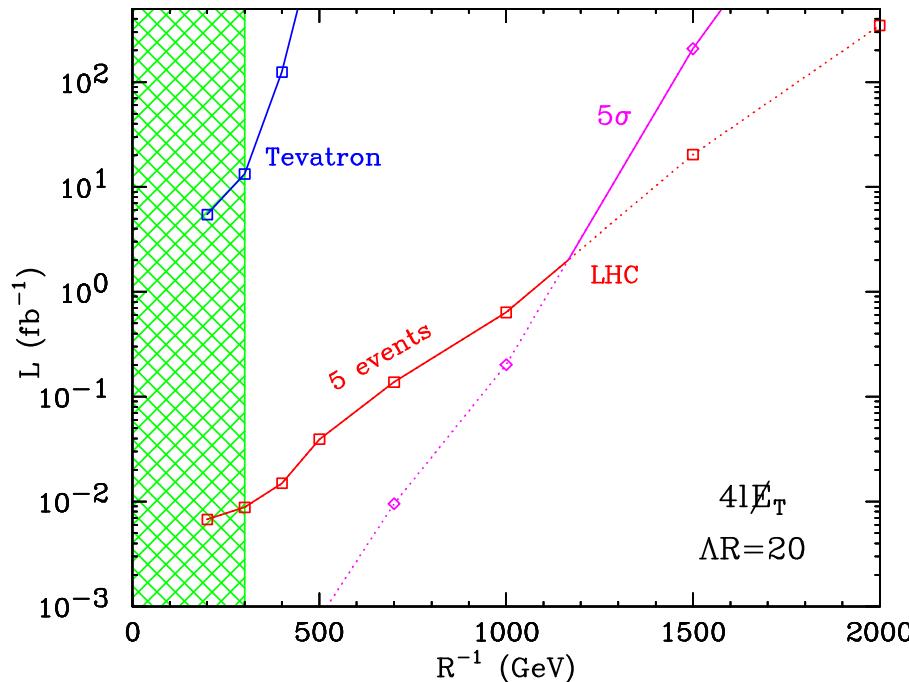
Hooper and Profumo, Phys.Rept.453:29-115,2007

- Tevatron: CDF, Run IB

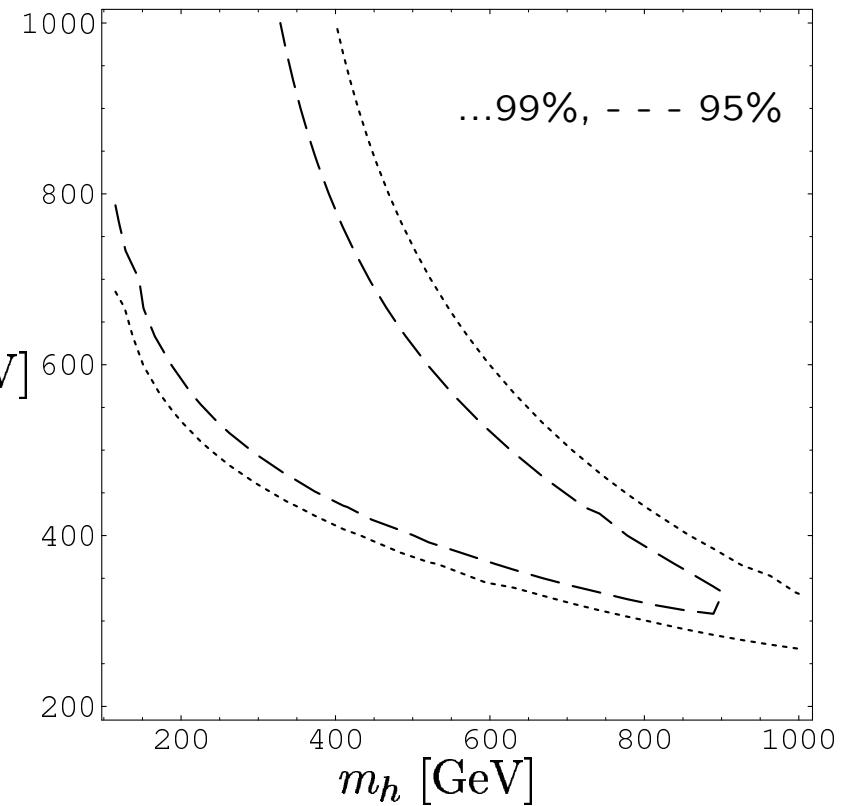
$m_{KK} \gtrsim 280$  GeV

Lin, 2005

- LHC Prospects:



$R^{-1} [\text{GeV}]$



...99%, - - - 95%

Cheng, Matchev, Schmaltz,  
Phys.Rev.D66:056006,2002

# Warped Models

- The Randall-Sundrum (RS) Model

- 5D warped model of hierarchy,  $M_5 \sim M_P$ .

Randall, Sundrum, 1999

- A slice of  $\text{AdS}_5$  spacetime.

- Negative constant curvature.
- Flat boundaries: Planck (UV) and TeV (IR) branes.
- Gravity UV-localized, SM on TeV-brane.
- AdS/CFT: Dual geometric picture of strong dynamics.

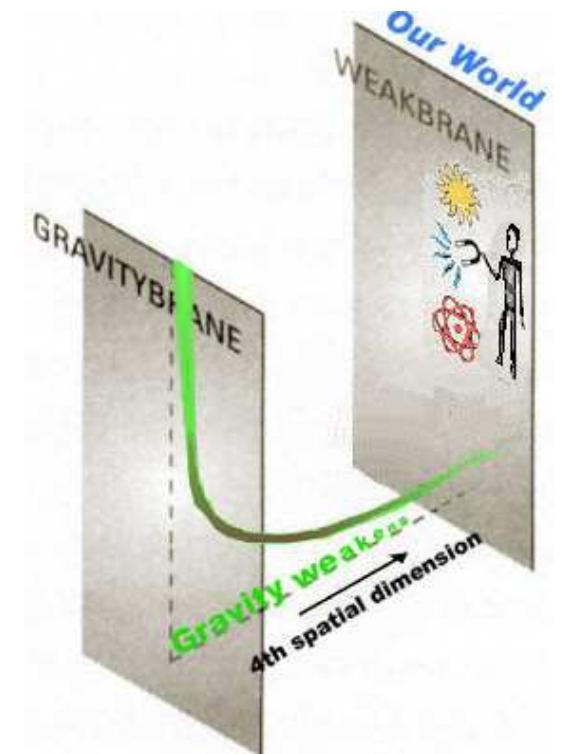
Maldacena, 1997

- Metric:  $ds^2 = \underbrace{e^{-2ky}}_{\text{warp factor}} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$ .

- $k \lesssim M_5$  and  $y \in [0, \pi r_c]$ .

- Redshift:  $e^{-krc\pi} \langle H_5 \rangle \sim m_W$ ; IR-localized Higgs,  $\langle H_5 \rangle \sim k$ .

- $k\pi r_c \approx 35$ ; hierarchy via exponentiation.



# RS Signatures with SM on the Wall

- TeV-scale tower of KK gravitons.

- KK masses  $m_n = x_n k e^{-k\pi r_c}$

$$x_n = 3.83, 7.02, \dots$$

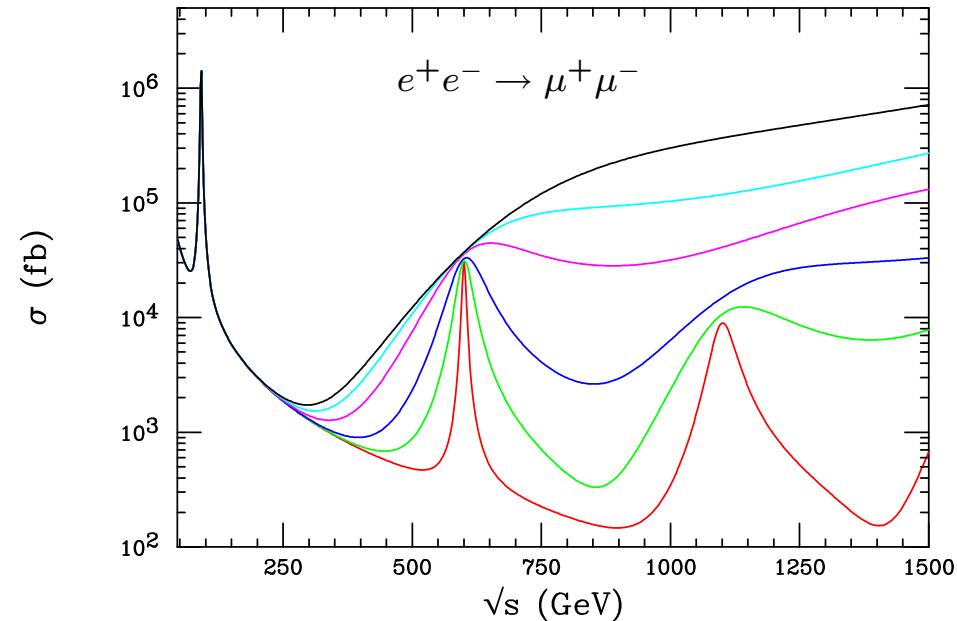
- Coupling to SM-brane:  $\sim \text{TeV}^{-1}$ .

- KK graviton spin-2 resonances.

- Decay into  $e^+e^-$ ,  $\gamma\gamma$ , ...

- Distinct signature.

H.D., Hewett, Rizzo, 1999



- Stabilized geometry → Radion scalar

- Typically lighter than KK modes.

- Couplings similar to Higgs.

- Can mix with Higgs through curvature-scalar coupling.

Goldberger, Wise, 1999

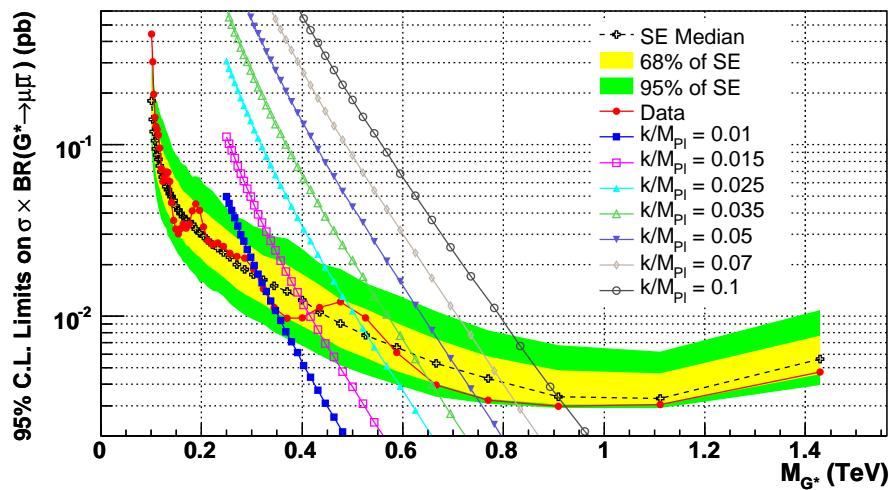
Csáki, Graesser, Kribs, 1999

# Tevatron Bounds and LHC Prospects

CDF Collaboration (Aaltonen *et al.*); di-muon channel

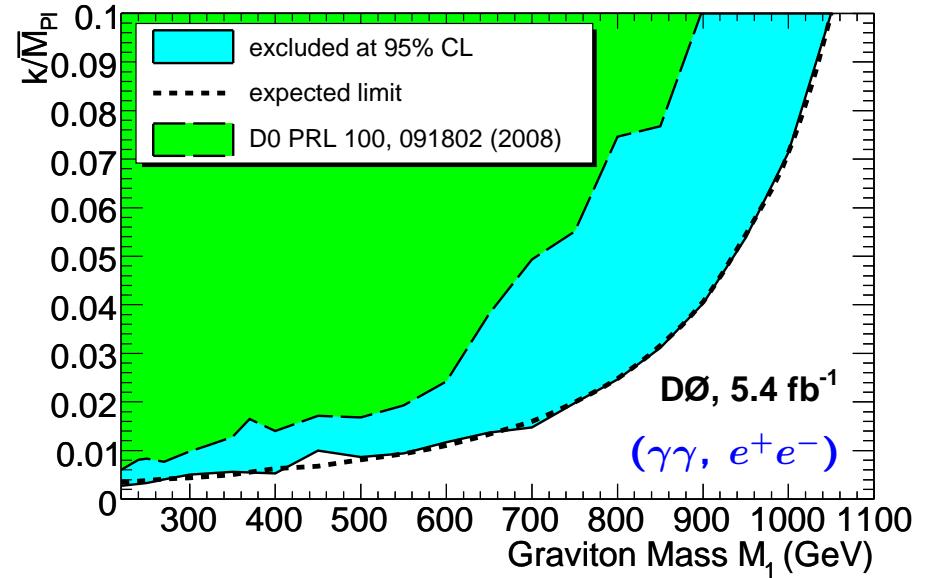
Phys.Rev.Lett.102:091805,2009

$m_G > 921 \text{ GeV}$  for  $k/M_{Pl} = 0.1; 2.3 \text{ fb}^{-1}$



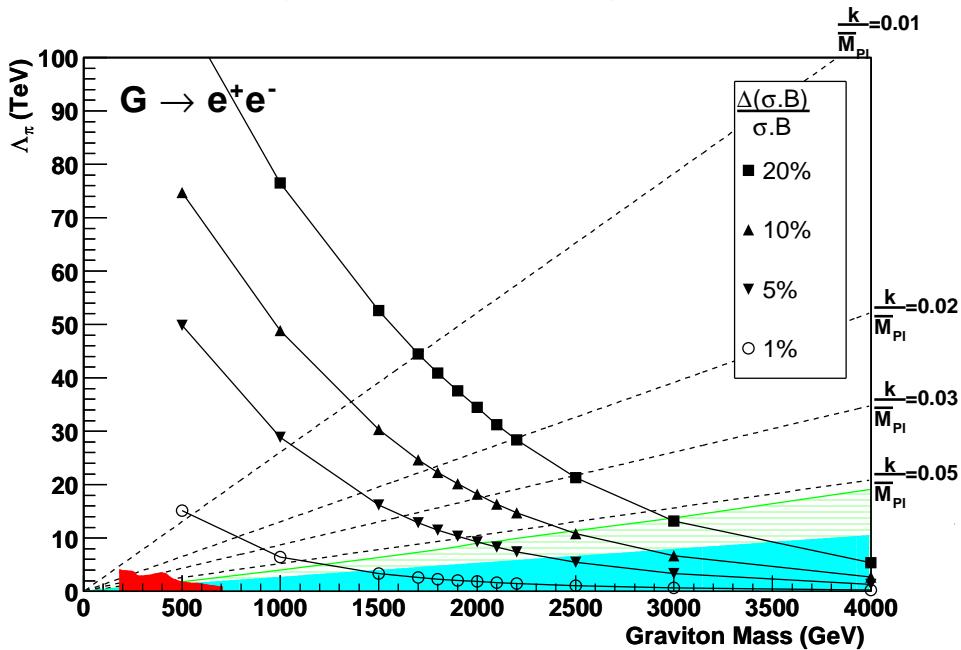
D0 Collaboration (Abazov *et al.*)

Phys.Rev.Lett. 104 (2010) 241802



- ATLAS:  $100 \text{ fb}^{-1}$ , 3.5 TeV for  $k/M_P \simeq 0.1$ .

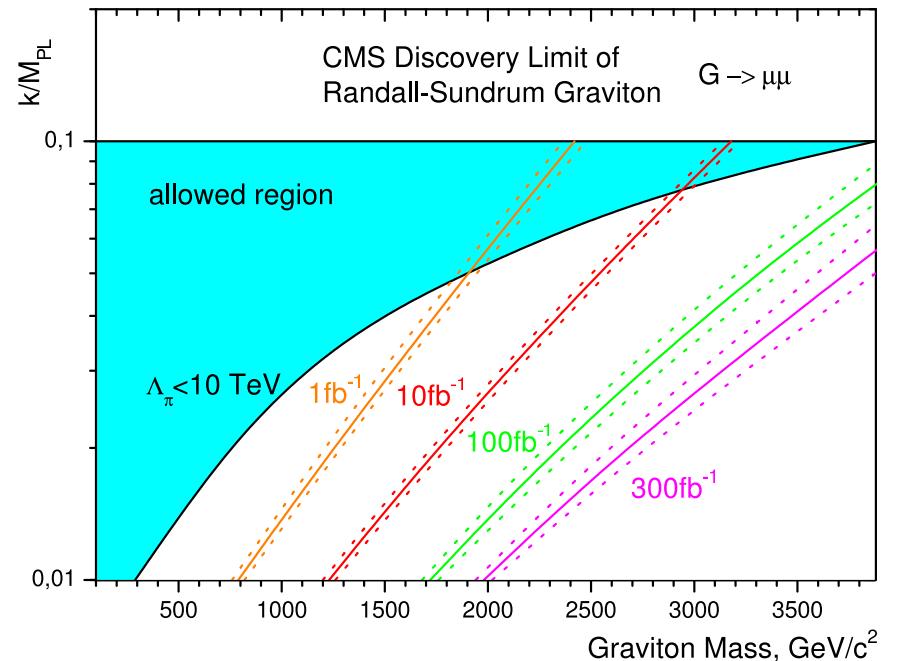
Allanach *et al.*, JHEP 0212:039, 2002



- CMS:

$100 \text{ fb}^{-1}$ , 4 TeV for  $k/M_P \simeq 0.1$ .

Belotelov *et al.*, CMS Note 2006/104



# The RS Model with 4D SM (1999)

## Pros:

- Natural Planck-weak hierarchy.
- Striking signals.

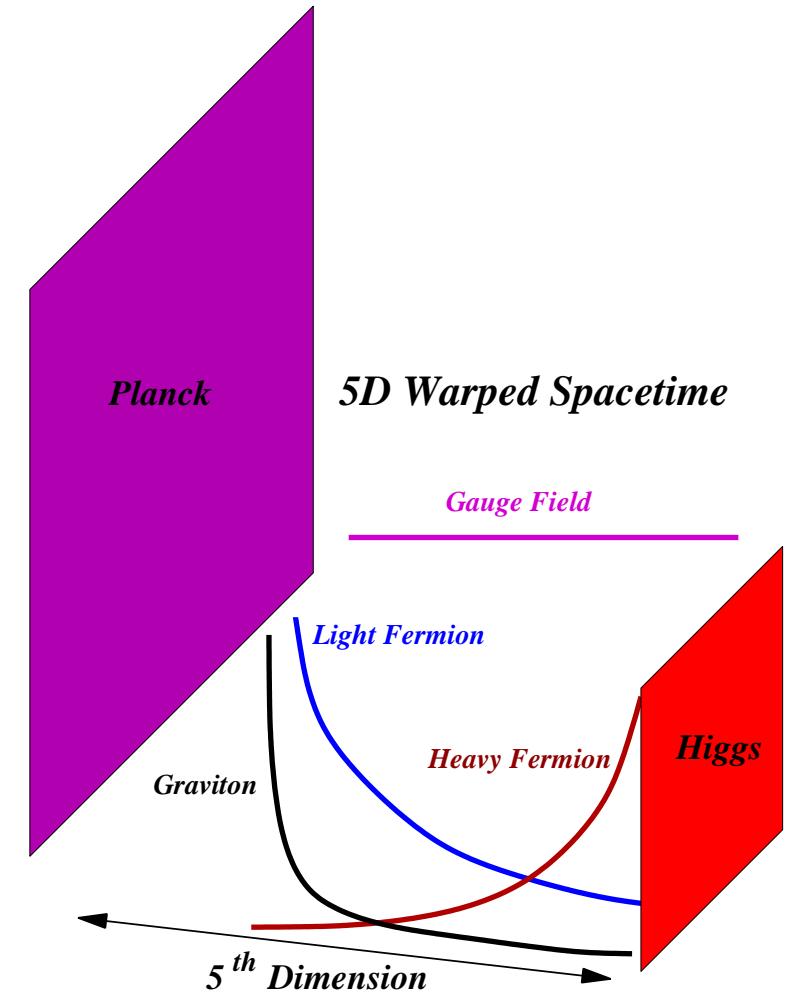
## Cons:

- Dangerous operators: Large IR cutoff-scales → little hierarchy.
- Flavor still a mystery.

# SM Flavor from a Warped Bulk

- 5D fermion masses,  $m/k \sim 1 \rightarrow$  localization. Grossman, Neubert, 1999
- UV(IR)-localization (overlap with Higgs)  $\rightarrow$  Light (heavy) fermion.
- UV-localization: Large effective cutoff scales. Gherghetta, Pomarol, 2000
- $\therefore$  Unwanted light flavor operators suppressed.

- Modified KK couplings.
  - Gauge KK couplings:  $(k\pi r_c \approx 35)$
  - UV-brane (e.g.  $e, u$ ):  $\sim g/\sqrt{k\pi r_c}$
  - IR-brane (e.g.  $H, t_R$ ):  $\sim g\sqrt{k\pi r_c}$
- Graviton KK couplings in  $\sim \text{TeV}^{-1}$ :
  - Light fermions:  $\sim$  Yukawa.
  - IR-brane (e.g.  $H, t_R$ ):  $\sim 1$ .
  - Gauge fields ( $g, \gamma$ ):  $\sim 1/(k\pi r_c)$ .



- Collider Signals: more challenging.
  - Important production and decay channels suppressed.

# Constraints on Warped Hierarchy/Flavor Models

- Control  $\delta T$ : 5D custodial  $G_c = SU(2)_L \times SU(2)_R \times U(1)_X$ .

Agashe, Delgado, May, Sundrum, 2003

- $Zb\bar{b}$ :  $G_c \times \mathbb{Z}_2$  Agashe, Contino, Da Rold, Pomarol, 2006

- Gauge KK mass  $m_{KK} \gtrsim 2 - 3$  TeV. Carena, Pontón, Santiago, Wagner, 2007

- KK gluon exchange contribution to  $\epsilon_K$ :

Agashe, Perez, Soni, 2004

Csaki, Falkowski, Weiler, 2008

- $m_{KK} \gtrsim 20$  TeV;  $\mathcal{O}(30\%)$  uncertainty

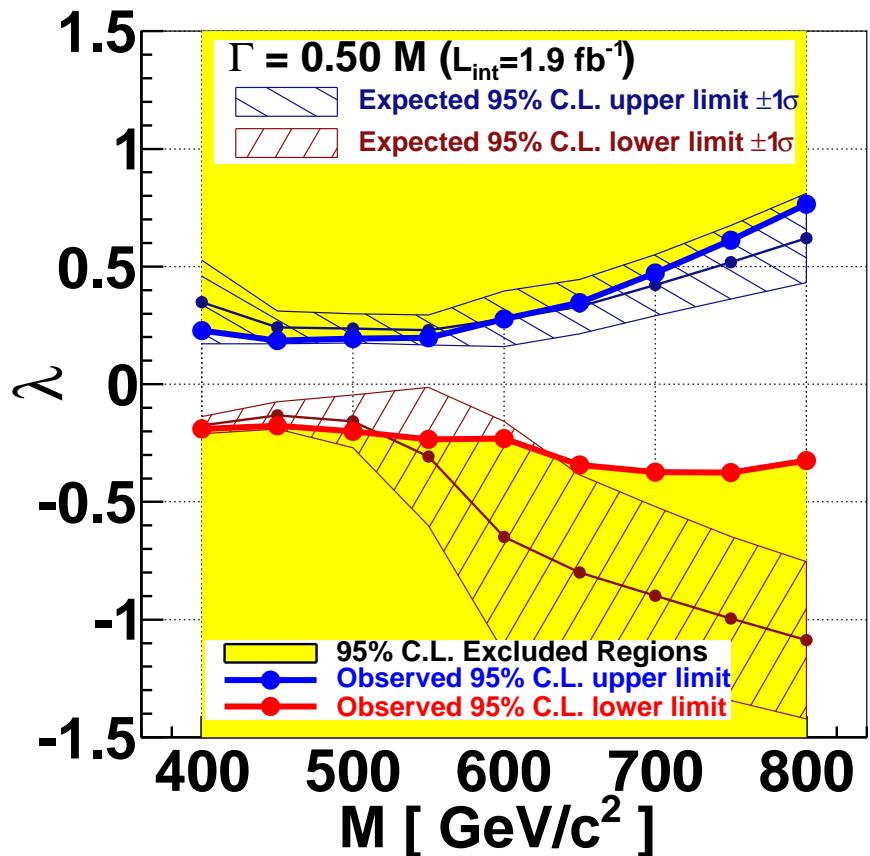
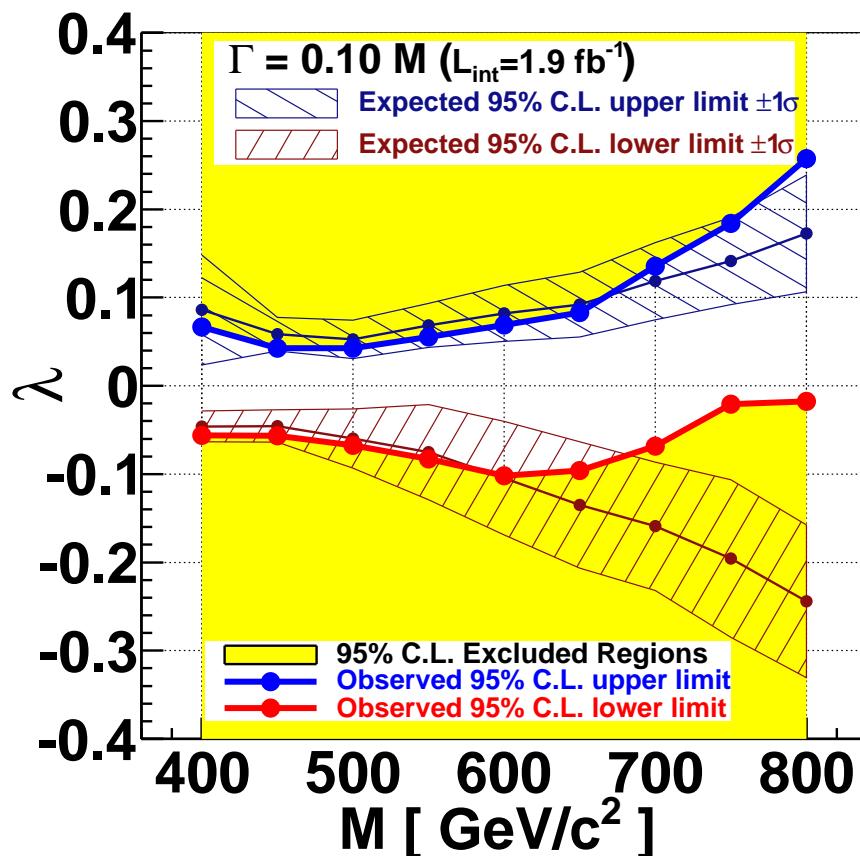
Further 5D flavor structure for  $m_{KK} \sim$  TeV. *E.g.* Fitzpatrick, Perez, Randall, 2007

# Collider Signals and Realistic Bulk Flavor

- The basic RS signals need to be revisited.
  - KK gluons:
    - Agashe, Belyaev, Krupovnickas, Perez, Virzi, 2006
    - Lillie, Randall, Wang, 2007
  - Production from light quark initial states, suppressed.
  - Decay mostly to  $t\bar{t}$ ,  $\Gamma_{KK} \sim m_{KK}/6$ .
  - Top-polarization (different  $t_L$  and  $t_R$  KK gluon couplings) a handle.
  - LHC reach 3-4 TeV with  $100 \text{ fb}^{-1}$ .
  - ★ Light  $t^1$  ( $SU(2)_L \times SU(2)_R \times \mathbb{Z}_2$  models):
    - Favored by EW data.
- Carena, Pontón, Santiago, Wagner, 2006
- Larger  $\Gamma_{KK}$ , reduced  $\text{BR}(g^1 \rightarrow t\bar{t})$ .
- Carena, Medina, Panes, Shah, Wagner, 2008

- Search for vector color-octet  $t\bar{t}$  resonances:

CDF Collaboration (T. Aaltonen *et al.*)  
 Phys.Lett. B691 (2010) 183-190



$$\lambda = \lambda_q \lambda_t \text{ (in units of } g_s).$$

- KK gravitons:

Fitzpatrick, Kaplan, Randall, Wang, 2007

Agashe, H.D., Perez, Soni, 2007

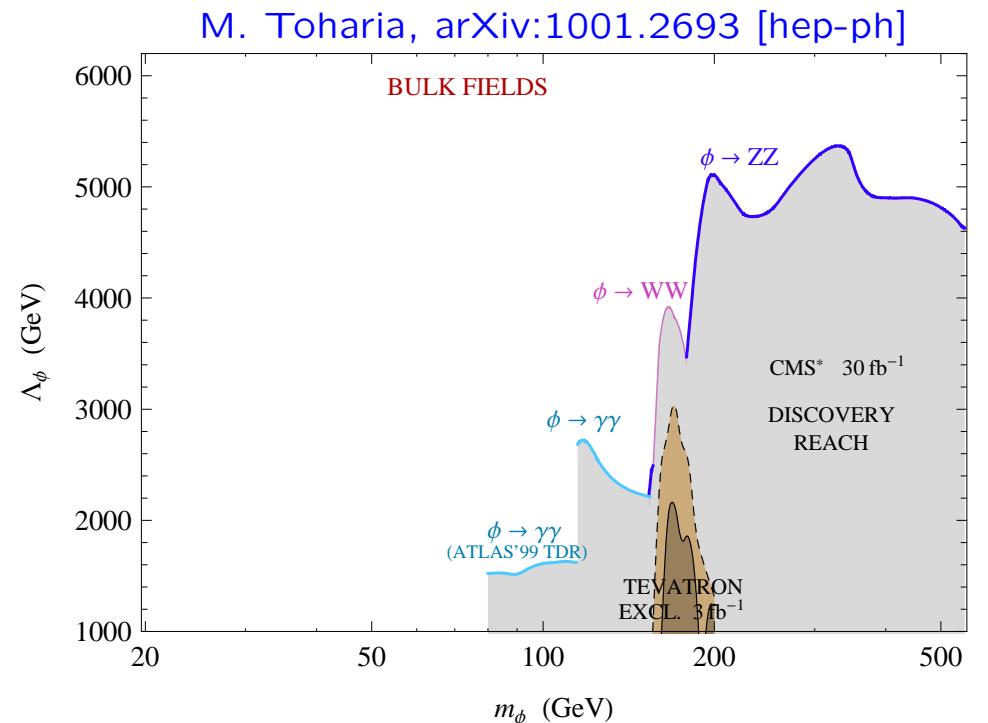
- Distinct RS signal.
- Production through  $gg$  initial state, volume suppressed.
- Golden (dilepton, diphoton) modes negligible.
- Decay through the Higgs (including  $Z_L/W_L$ ) and top sectors.
- $gg \rightarrow G^1 \rightarrow Z_L Z_L \rightarrow 4\ell \Rightarrow$  LHC reach  $\lesssim 2$  TeV with  $300 \text{ fb}^{-1}$ . ADPS, 2007
- $Z \rightarrow jj$  highly boosted ( $E \sim 1$  TeV), dominated by  $Z + j$  background.

- The Radion:

- Associated with fluctuations of  $r_c$ .
- Typically the lightest new 5D state.
- 5D SM: new tree-level couplings.

Csáki, Hubisz, Lee, 2007

LHC reach from Higgs projections →



- The electroweak sector:
  - 5D  $SU(2)_L \times SU(2)_R \times U(1)_X$  to accommodate EW precision data.
  
- $Z'$ : [Agashe, et al., 2007](#)
  - At the TeV scale, 3 neutral states, collectively denoted by  $Z'$ .
  - Production dominated by light quark initial states.
  - Main decay channels IR-brane fields:  $H$ ,  $W_L/Z_L$ ,  $t$ .
  - $Z' \rightarrow W_L^+ W_L^- \rightarrow \ell^+ \ell^- E_T$ : LCH reach 2 TeV with  $100 \text{ fb}^{-1}$ .
  - $W \rightarrow jj$  boosted dijet challenge, requires more detailed analysis.
  - $t\bar{t}$  dominated by KK gluon “background.”
  
- $W'$ : [Agashe, Gopalakrishna, Han, Huang, Soni , 2008](#)
  - 4 Charged states.
  - No KK gluon pollution.
  - LHC reach similar to  $Z'$ .
  - Reach may be improved by better control over reducible backgrounds.

## Models without a Higgs

- Higgsless models: EWSB via boundary conditions.

Csaki, Grojean, Murayama, Pilo, Terning, 2003

Csaki, Grojean, Pilo, Terning, 2003

- Deconstruction

Foadi, Gopalakrishna, Schmidt, 2003

Chivukula, He, Kurachi, Simmons, Tanabashi, 2004

- Quark condensation: KK gluon-mediated.

Burdman, Da Rold, 2007

Bai, Carena, Pontón, 2008

- Composite  $W/Z$  models.

Cui, Gherghetta, Wells, 2009

# Little Randall-Sundrum (LRS) Models

H.D., Perez, Soni, 2008

- RS as a model of flavor:  $M_5 \ll M_P$  viable option.
- $M_5 \gg \text{TeV}$  needed to suppress unwanted (FCNC, ...) operators.
- Volume-truncated RS models:  $1 \ll kr_c\pi \ll 35$ .
- Truncation: some unwanted contributions suppressed.

Example: tree-level oblique parameter  $T_{\text{tree}} \propto kr_c\pi$  in RS models.

(5D custodial symmetry to suppress  $\delta T$  from UV-sensitive loops.)

- Explain  $\langle H \rangle / M_5 \ll 1$  hierarchy  $\Rightarrow$  warped TeV-scale KK modes.
- LRS: significant improvement in *clean* collider signals.

Example:  $S \sim \sigma(q\bar{q} \rightarrow Z' \rightarrow \ell^+\ell^-) \propto 1/(kr_c\pi)^3$ .

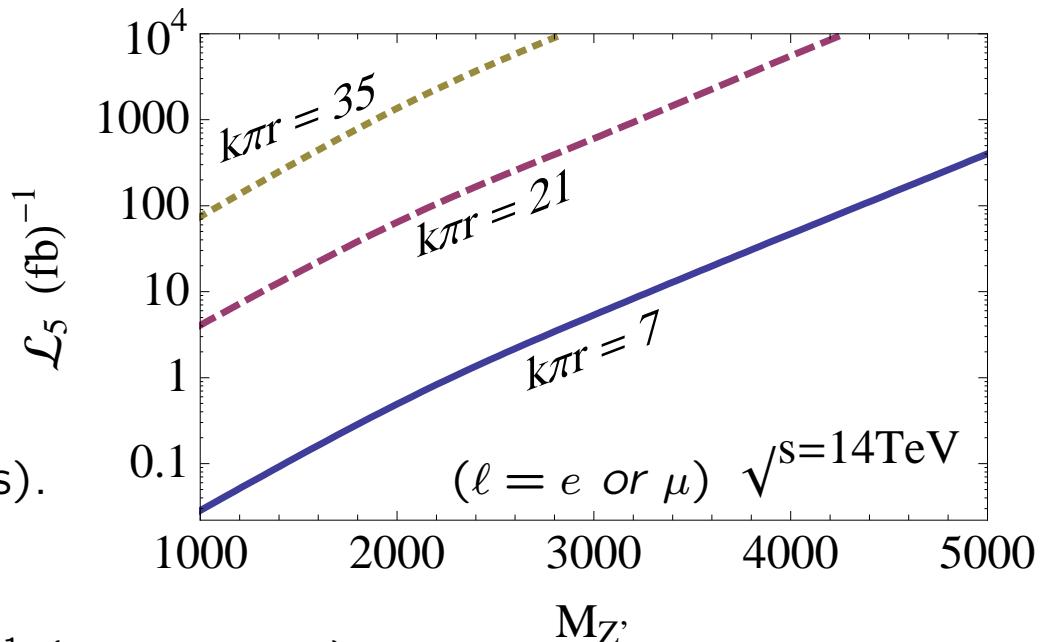
- Flavor constraints on LRS from  $\epsilon_K$ :  $k\pi r_c \gtrsim 7$  ( $M_5 \gtrsim 10^4$  TeV).

Bauer, Casagrande, Grunder, Haisch, Neubert, 2008

- LHC Reach for Little  $Z'$  in  $\ell^+\ell^-$

- Couplings to  $q, \ell \propto 1/\sqrt{kr_c\pi}$ .
- $|\eta_\ell| < 3.0, p_{T_\ell} > 100$  GeV.
- $M_{\ell^+\ell^-}$  within  $M_{Z'} \pm 100$  GeV.
- Background irreducible SM.
- $\mathcal{L}_5$ :  $\int L dt$  for  $5\sigma$  signal ( $\geq 3$  events).
- Original RS ( $kr_c\pi \approx 35$ ):

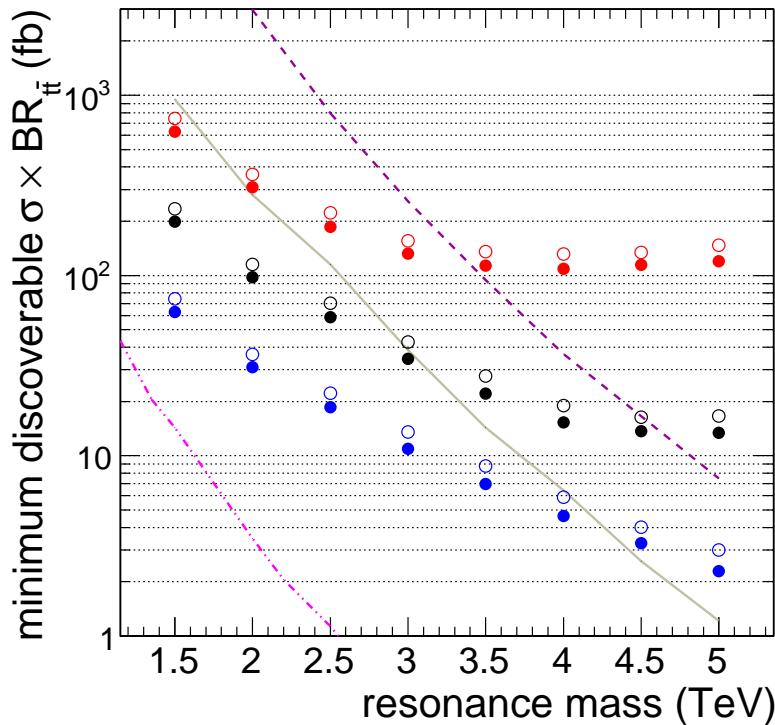
$M_{Z'} \approx 3$  TeV,  $\sqrt{s} = 14$  TeV, 300 fb $^{-1}$  (any channel).



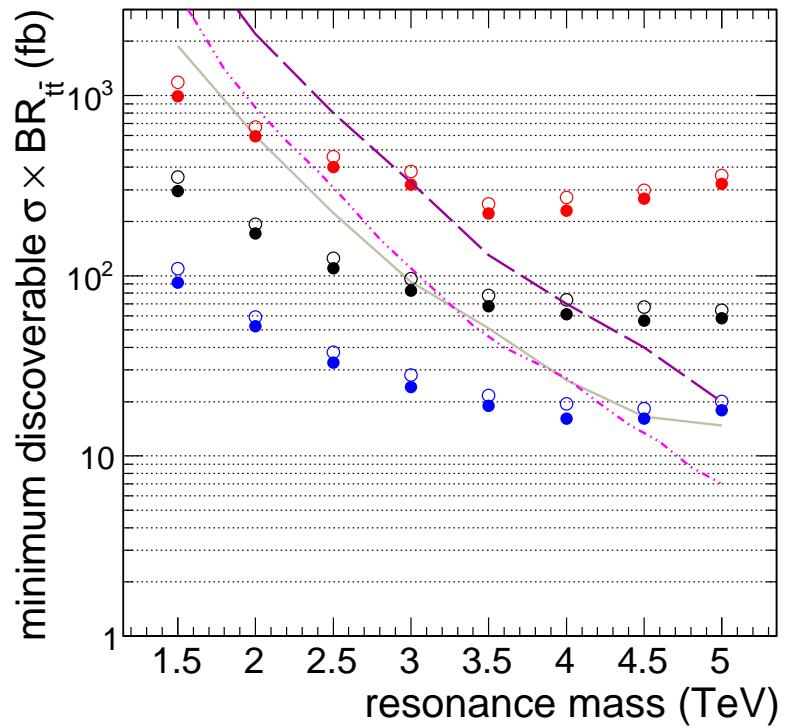
- Little KK gluons:  $pp \rightarrow t\bar{t} \rightarrow bW(jj)\bar{b}W(\ell\nu)$
- Same enhanced *production* (coupling to  $q\bar{q}$ ) for  $g^{(1)}$ .
- $5\sigma$  estimates for 3-TeV KK gluon at  $\sqrt{s} = 14$  TeV (following ABKPV, 2006):

(2,8,21) fb $^{-1}$  for  $kr_c\pi = (7, 21, 35)$

### Narrow Width



### 15% Width



From: K. Rehermann, B. Tweedie, arXiv:1007.2221 [hep-ph].

- LHC:  $\sqrt{s} = 14$  TeV, discovery:  $5\sigma$ ,  $N_S > 10$ .

Chiral resonances:  $\circ$ : left-handed;  $\bullet$ : right-handed; (1, 10, 100) fb<sup>-1</sup>

- Boosted semi-leptonic tops;  $\mu +$  jets using new cuts.
- Left, dashed : LRS KK gluons.
- Right: RS KK gluons; Lillie, Randall, Wang, 2007 (dashed); ABKPV (dot-dashed).

# The Little Radion

- Typically,  $m_\phi < m_{KK}$ , potential first glimpse of BSM.
- Couplings suppressed by  $\Lambda_\phi \gtrsim 1$  TeV (4D cutoff scale).

$$\Lambda_\phi \equiv e^{-kr_c\pi} \sqrt{6M_5^3/k}$$

- 5D SM:  $\phi gg$ ,  $\phi\gamma\gamma$  couplings depend on  $1/(kr_c\pi)$ :

Csáki, Hubisz, Lee, 2007

- $gg \rightarrow \phi \rightarrow \gamma\gamma$ : enhanced in LRS ( $kr_c\pi \ll 35$ ).
- Important below  $WW$  threshold.
- Diphoton coupling:
  - Clean signal.
  - Largely insensitive to 5D details.
  - Dependence on  $kr_c$  potential handle on UV physics.

⇒ **Little radion an interesting target for the 7-TeV LHC run.**

# Collider Reach

Lower curves: Tevatron  $2\sigma$  reach

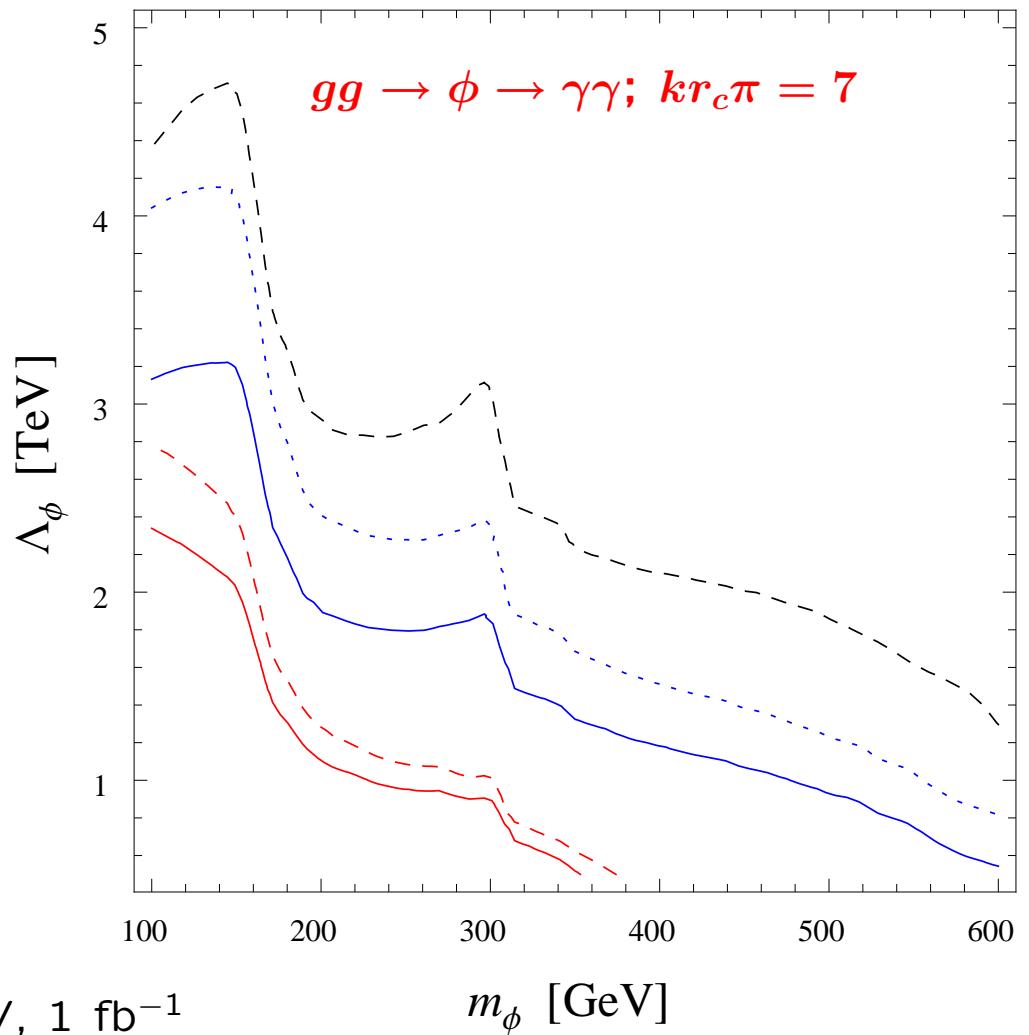
- $5 \text{ fb}^{-1}$  (solid),  $10 \text{ fb}^{-1}$  (dashed)
- Photon ID: 70%
- $p_T > 25 \text{ GeV}$ ,  $|\eta| < 1.1$ ,  $\Delta R > 0.4$
- $|m_{\gamma\gamma} - m_\phi| < 10 \text{ GeV}$
- $E_T^{had} < 10 \text{ GeV}$  within  $\Delta R = 0.4$

Middle curves: LHC

- $\sqrt{s} = 7 \text{ TeV}$ ,  $1 \text{ fb}^{-1}$
- $5\sigma$  (solid),  $3\sigma$  (dotted)
- Photon ID: 80%, same isolation
- $p_T > 30 \text{ GeV}$ ,  $|\eta| < 2.4$ 
  - (ATLAS Higgs search)

Upper curve: LHC,  $5\sigma$ ,  $\sqrt{s} = 14 \text{ TeV}$ ,  $1 \text{ fb}^{-1}$

H.D., McElmurry, Soni, arXiv:1009.0764 [hep-ph]



## Dual 4D Description (AdS/CFT) Maldacena, 1997

- Warped models: conformal ( $\text{AdS}_5$ ) dynamics below the UV scale (brane) spontaneously broken at the IR scale (brane).

Arkani-Hamed, Porratti, Randall, 2000; Rattazzi, Zaffaroni, 2000

- TeV-scale strong dynamics  $\Rightarrow$  Resonances (KK modes)
- Naturally light Goldstone dilaton (radion) associated with dilations (size of the fifth dimension).
- Original RS: UV scale near  $\bar{M}_P$ .
  - Dynamical *conformal depth*:  $\sim 1 \text{ TeV} \leftrightarrow \sim \bar{M}_P$ .
- LRS: UV (flavor) scale  $M_5 \gtrsim 10^3 \text{ TeV}$ .
  - Dynamical conformal depth:  $\sim 1 \text{ TeV} \leftrightarrow \sim M_5$ .

Some recent works on light dilaton physics:

Goldberger, Grinstein, Skiba, 2007; Fan, Goldberger, Ross, Skiba, 2008; Appelquist, Bai, 2010

# Conclusions

- Extra dimensions: possibilities for hierarchy and more.
  - New phenomena at the TeV scale.
- Discovery a fundamental revolution in science.
- Various extra dimensional scenarios can be tested at the LHC.
- Signals could be more subtle or elusive than the first estimates.

Examples:

- LED: Black hole signals could be less obvious/likely.
- Warped models of hierarchy and flavor:
  - \* Signals likely more challenging than in original models, mass scales larger.
  - \* Larger  $m_{KK}$ : boosted dijets from decays ( $E \gtrsim 1$  TeV), mono-jet backgrounds.
- Truncated warped bulk (conformal depth)  $\leftrightarrow$  Enhanced clean signals.
- Observing TeV-scale KK modes: is Planck-weak hierarchy addressed?
- Little RS models: possible clues may be accessible at the LHC.